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Assessment of water-limited winter wheat yield potential at spatially contrasting sites in Ireland using a simple growth and development model

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Abstract

Although Irish winter wheat yields are among the highest globally, increases in the profitability of this crop are required to maintain its economic viability. However, in order to determine if efforts to further increase Irish wheat yields are likely to be successful, an accurate estimation of the yield potential is required for different regions within Ireland. A winter wheat yield potential model (WWYPM) was developed, which estimates the maximum water-limited yield achievable, within the confines of current genetic resources and technologies, using parameters for winter wheat growth and development observed recently in Ireland and a minor amount of daily meteorological input (maximum and minimum daily temperature, total daily rainfall and total daily incident radiation). The WWYPM is composed of three processes: (i) an estimation of potential green area index, (ii) an estimation of light interception and biomass accumulation and (iii) an estimation of biomass partitioning to grain yield. Model validation indicated that WWYPM estimations of water-limited yield potential (YP_w) were significantly related to maximum yields recorded in variety evaluation trials as well as regional average and maximum farm yields, reflecting the model's sensitivity to alterations in the climatic environment with spatial and seasonal variations. Simulations of YP_w for long-term average weather data at 12 sites located at spatially contrasting regions of Ireland indicated that the typical YP_w varied between 15.6 and 17.9 t/ha, with a mean of 16.7 t/ha at 15% moisture content. These results indicate that the majority of sites in Ireland have the potential to grow high-yielding crops of winter wheat when the effects of very high rainfall and other stresses such as disease incidence and nutrient deficits are not considered.

Keywords

model • radiation use efficiency • yield gap • yield potential

Introduction

Increases in the profitability of winter wheat production in Ireland are required to maintain the economic viability of this crop, which is under pressure due to recent variability in grain prices and high crop input costs (Thorne, 2016), despite Irish winter wheat yields being among the highest globally (Burke *et al*., 2011; Food and Agriculture Organization of the United Nations [FAO], 2016). Attempts by growers to achieve increased yields are a common method employed to reduce the likelihood of crop profit losses and to meet the projected increase in grain demand from future increases in the global population size (Department of Agriculture, Food and the Marine [DAFM], 2015). However, annual increases in the average winter wheat yield in Ireland have slowed in recent times and may have plateaued (Central Statistics Office [CSO], 2016), which casts doubt on whether striving for yield increases is likely to be successful.

In the absence of new legislative restrictions or large changes in cropping area, this plateauing of yield may be a result of one or more of the following reasons: due to slowing in the development of applicable new technologies, alterations in land use, the origin of new or previously underrated limitations or the gap between yield potential (YP) and achieved yield becoming minimal (Grassini *et al*., 2013), with Van Wart *et al*. (2013) describing the continuous reduction in the likelihood that profitable increases in yield can be achieved when farm yields move closer to the maximum yield achievable. Therefore, in order to accurately estimate the most suitable method to further increase the viability of winter wheat in Ireland, an estimation of water-limited YP (YP_w), in the context of typical crop development and varieties currently available, is required to evaluate the magnitude of the difference between average farm yield and YP_w.

Previous estimates of wheat YP (either water-limited or unlimited) for Ireland have been relatively rare and have quite a large range, from 11.8 to 22.8 t/ha (Supit *et al*., 2010; Burke *et al*., 2011; Boogaard *et al*., 2013). This large variation is partially a

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reflection of different approaches to calculating the YP and their inherent differences in the definition of the measured value, which can vary considerably between studies (Fischer, 2015). Studies that have reported values at the higher section of the range for either the Republic of Ireland or Northern Ireland (Burke *et al*., 2011; Sylvester-Bradley and Kindred, 2014) have estimated the YP based on a utilisation rate of a standard proportion of the incident radiation. These estimates, therefore, do not account for the effect of temperature on development or the daily variation in incident radiation, aspects that can be variable in the Irish climate (Sweeney, 2014). In contrast, studies that have estimated values at the lower portion of the range (Supit *et al*., 2010; Boogaard *et al*., 2013) have been based on crop models with parameters for crop growth and development based on studies from other countries with more extensive availability of this data, such as the UK. Furthermore, these studies focus on much larger-scale areas than Ireland, typically Europe or greater, and therefore the ability to investigate the spatial differences within Ireland in detail is quite limited.

Van Ittersum *et al*. (2013) detailed the requirement for a "bottom–up" approach to modelling yield gaps and YP, based on daily step simulation, to allow for a localised set of parameters and a more accurate estimation. Thus, a similar method of estimating the maximum yield achievable, within the confines of current genetic resources and technologies, for spatially contrasting regions in Ireland is required.

This article describes the development of a simple winter wheat water-limited yield potential model (WWYPM), using parameters for winter wheat growth and development observed recently in Ireland, and a minor amount of daily meteorological input to allow for spatially robust estimations. The aim of the study was to investigate the variation in YP_w of winter wheat crops at contrasting sites in Ireland.

Model overview

The WWYPM is composed of three processes: (i) estimation of the potential green area index (GAI) of a winter wheat crop based on the accumulation of thermal time (degree days above a base of 0°C) on each day of the growing season and the latitude of the site, (ii) an estimation of the potential water-limited biomass assimilation based on the amount of photosynthetically active radiation (PAR) intercepted and the plant-available water capacity (PAWC) on each day of the growing season and (iii) the estimation of the proportion of assimilated biomass that is available for grain production based on the thermal time profile during the growing season. Estimations are based on the interactions between daily recordings of meteorological data (maximum and minimum temperature, incident solar radiation and rainfall), latitude and selected indices of crop growth and development as observed in winter wheat crops intensively monitored over a period of 3 yr at three locations across the island of Ireland. Detailed information on the management of these crops is described by Lynch *et al*. (2017).

Potential GAI estimation

Wheat crop development is largely influenced by temperature and photoperiod (Slafer and Rawson, 1994; Porter and Gawith, 1999), with Sylvester-Bradley *et al*. (2008) observing that average wheat crops grown in the UK incurred three primary stages of canopy development: a foundation phase with an initial slow increase in GAI based on leaf production and tillering; a construction phase in which a rapid increase occurs due to stem extension and leaf expansion; and a production phase after anthesis as senescence of the crop occurs. Therefore, estimations of canopy development in the WWYPM are primarily dictated by thermal time accumulated during the season, along with the Julian day upon which the day length (DL; time between sunrise and sunset) reaches 14 h or greater at the subject site (DL_{14}). The interaction between photoperiod and crop development can vary considerably with genotype, with many crop models providing detailed estimations of the influence of photoperiod on stem elongation and crop development (Jamieson *et al*., 2007; Reynolds *et al*., 2012). However, similar information is unavailable for Irish conditions and the inclusion of a complex sub-model for photoperiod effect may negate the efforts to develop a "simple" model that does not require a high degree of input variables. Therefore, in order to accommodate this impact of DL on crop development, the DL_{14} is used to reflect the earliest potential onset of stem extension (growth stage [GS]31) in the evaluated crop, as an established association exists between DL and crop development until terminal spikelet (McMaster *et al*., 2008). This selection of 14 h DL as the key value in this regard is an assumption based on the earliest observed onset of GS31 for crops monitored at contrasting sites on the island of Ireland for the study outlined in Lynch *et al*. (2017), with DL at GS31 ranging from 13.8–16.4 h (unpublished data).

Daily values of degree days (°C days) were calculated from the maximum and minimum daily temperatures (T_{max} and T_{min}, respectively), with a base temperature of 0°C using the following equations:

$$\text{If } T_{\min} > 0°\text{C}: \quad °\text{C days} = \frac{T_{\max} - T_{\min}}{2}$$

$$\text{If } T_{\min} < 0°\text{C}: \quad °\text{C days} = \left(\frac{T_{\max} - 0}{2}\right) - \left(\frac{0 - T_{\min}}{4}\right)$$

$$\text{If } T_{\max} < 0°\text{C}: \quad °\text{C days} = 0$$

The Julian date when DL was greater than 14 h (DL_{14}) was determined by calculating the typical DL from the latitude of the site as described by McMurtrie (1993).

The calculation of the daily value of GAI is based on the observed values for GAI and degree days at key stages of crop development, as measured for monitored winter wheat crops in Ireland (Table 1). As such, the WWYPM estimates GAI based on six separate phases of development: (i) sowing to GS30, (ii) GS30–GS31, (iii) GS31–GS61, (iv) GS61–GS69, (v) GS69–GS87 and (vi) GS87 to senescence. The duration of each phase is primarily determined by the number of days required for a site to accumulate the corresponding degree days, with the daily GAI value estimated based on an interpolation between the start and end dates of each period.

In order to account for vernalisation of the crop, cumulative vernalisation days (V_{days}) were calculated using the equations proposed by Spink *et al*. (2000b). Briefly, a crop accumulates one V_{day} when the daily mean temperature is within the range 3–10°C, while a proportionally lower V_{day} is acquired if the daily mean temperature is within either of the ranges –4 to 3°C or 10 to 17°C:

$$\text{If mean daily temperature is} > 3 \text{ and} \leq 10°\text{C}, \; V_{\text{days}} = 1$$

$$\text{If mean daily temperature } (x) \text{ is} > -4 \text{ and} \leq 3°\text{C},\!: \; V_{\text{days}} = \frac{x+4}{7}$$

$$\text{If mean daily temperature } (x) \text{ is} > 10 \text{ and} \leq 17°\text{C}; \; V_{\text{days}} = \frac{17-x}{7}$$

$$\text{If mean daily temperature is} < -4°\text{C}, \text{ or} > 17°\text{C}, \text{ then } V_{\text{days}} = 0$$

For simulations at sites where 50 cumulative V_{days} are not incurred before 1,231 degree days are accumulated, the crop's estimated GAI value remains constant at 2.4 until the crop is adequately vernalised. During this period of constant GAI, degree days accumulated do not contribute to the GS31–GS61 phase.

Table 1. Indices of thermal time and GAI development used in the winter wheat yield potential model

Periods of development	GAI progression	Thermal time (°C days)
Sowing to GS30	0.0–1.7	1118
GS30–GS31	1.7–2.4	113
GS31–GS61	2.4–6.7	453
GS61–GS69[1]	6.7–6.7	46
GS69–GS87	6.7–0.7	741
GS87 to senescence	0.7–0.0	233

[1]Allocated thermal time for the GS61–GS69 phase is an estimation of the duration of constant maximum GAI, as opposed to a reflection of the duration of anthesis.
GAI = green area index; GS = growth stage.

The development of GAI does not progress to the GS31–GS61 phase until DL_{14}, in order to account for the effect of photoperiod on the crop's development beyond the foundation phase of canopy development. In simulations whereby crops have accumulated 1,231 degree days prior to DL_{14}, the crop's estimated GAI value remains constant at 2.4 until DL_{14}, after which it progresses to the GS31–GS61 phase.

To account for poor canopy development in cooler seasons, crops that do not accumulate 1,231 degree days prior to DL_{14} incur a reduced GAI at GS61. This is due to the tendency for wheat crops with lower-than-average canopy after the majority of tillering has ended (GS31 onwards) to have lower-than-average canopies at anthesis, as the ability for a wheat crop's canopy to compensate for poor establishment is mainly due to an increased duration of tillering (Whaley *et al*., 2000). Therefore, for simulations wherein less than 1,231 degree days have been accumulated, the estimated GAI will increase for 453 degree days after DL_{14} to a maximum, which is reduced from 6.7 at the same proportion that the accumulated degree days was lower than 1,231 degree days on DL_{14}. Similarly, the daily decrease in GAI after the GS61–GS69 phase is in the same proportion as the differential between accumulated degree days at DL_{14} and 1,231 degree days.

The development of GAI is halted if the minimum daily temperature of the site falls to less than –5°C after the crop has entered the GS31–GS61 phase, due to the negative impact of such low temperatures to wheat development when the growing point of the plant is above the soil level (Spink *et al*., 2000a).

For simulations where sites do not accumulate the required degree days to reach the end of the GS87 to senescence phase before the 243rd Julian day (31 August or 30 August for a leap year) of the harvest year, the interpolation for the GS87-to-senescense phase is based on an estimated GAI of zero on the 243rd Julian day.

Potential total biomass estimation

As the availability of light and water are the two most important factors in determining the YP_w of winter wheat (Sylvester-Bradley and Kindred, 2014), the estimation of total water-limited biomass accumulation in the WWYPM is based on the interception of PAR and the use of PAWC by the crop.

Daily PAR was estimated as 0.5 × the daily incident solar radiation, as described by Bingham *et al*. (2007). The proportion of PAR that is intercepted by the canopy (light interception [LI]%) was estimated from the daily GAI estimate using Beer's law, assuming an extinction coefficient (k) of 0.5:

$$\text{LI\%} = 1 - e^{-k*GAI}$$

The daily total estimated intercepted PAR for the crop (PAR_{int}) was calculated from the LI% and the daily PAR estimation. An estimation of the water-unlimited daily biomass accumulation was subsequently calculated using a radiation use efficiency (RUE) value of 3.1 g/MJ per square metre:

$$\text{Biomass}\left(\text{g}/\text{m}^2\right) = \text{PAR}_{\text{int}}\ \text{x}3.1$$

This calculation is partially based on the findings of Monteith (1977), who reported that 2.8 g of biomass per megajoule of PAR is an achievable RUE for high-yielding cereal crops, with a modification based on the results from Irish monitor crops of winter wheat in recent times, which suggest that an RUE of 3.1 can be achieved in the highest-performing crops in Irish conditions (Lynch *et al*., 2017). Water-limited daily biomass accumulation is calculated similar to Berry *et al*. (2011), using a PAWC of 205 mm, which was calculated based on "heavy" soils with a high total AWC, such as loams, clay loams and silt clay loams (315 mm at a rooting depth of 1.5 m; Rowell, 1994; Berry *et al*., 2011), which are found in many regions across Ireland (Irish Soil Information System, 2017), with an estimated 0.65 of this water available to plants (Barraclough and Leigh, 1984). The PAWC is assumed to be at a constant maximum in any evaluated crop until 18 March, after which daily PAWC is calculated for each individual day (*j*) as:

$$PAWC_j = (AWC_{j-1} + R_j - UW_{j-1}) \times 0.65$$

where AWC_{j-1} is the residual AWC from the previous day, R_j is the daily rainfall and UW_{j-1} is the amount of water required to produce the total water-unlimited biomass on the previous day (calculated at a rate of 1 mm of PAWC per 5 g of biomass/m^2; Sylvester-Bradley *et al*., 2005). In simulations where $PAWC_j$ is zero or less than the required PAWC for that day's potential biomass growth, no biomass is accumulated on that date, or subsequent dates until adequate supplies of PAWC become available through rainfall, to simulate the potential effects of drought conditions. No further reductions in biomass accumulation are incurred by the simulated crops after PAWC has returned to values required for growth. This binary assumption for the relationship between daily biomass accumulation and PAWC has not been used in this manner previously, to the author's knowledge. It was selected partially due to the lack of detailed information on drought effects on cereal development in Irish conditions, as well as to allow for an indication of the potential impact of drought, while also facilitating high efficiency in biomass production after water availability increases, to avoid over-limiting YP.

Partitioning potential biomass to grain

As the vast majority of biomass accumulated after anthesis is partitioned to the grain (Jamieson *et al*., 1998; Lynch *et al*., 2017), all biomass accumulated during the GS69–GS87 and GS87-to-senescence phases are considered fully available for grain yield. Furthermore, previous studies have highlighted a variable concentration of water-soluble carbohydrates present in the stem component of the crop at anthesis (Ehdaie *et al*., 2006; Dreccer *et al*., 2013). Although the contributions of these assimilates to grain filling are also variable (Gent, 1994, Ehdaie *et al*., 2008) and can be negligible in crops that are grown without major degrees of stress (Savin and Slafer, 1991; Slafer, 2003), these assimilates are a potential source for grain filling and are therefore also considered a component for YP in the WWYPM. An estimation of these assimilates is calculated as 0.265 × total biomass accumulated during the GS31–GS61 phase, based on data reported by Sylvester-Bradley *et al*. (1998) for stem-soluble carbohydrate concentrations for monitor crops in the UK.

Model format, output and estimations from monitor crop data

All calculations for the WWYPM were conducted in Microsoft Excel 2010 (Microsoft Corporation, Albuquerque, NM, USA). The file required the input of daily minimum and maximum temperatures (in degrees Celsius), incident solar radiation (megajoule per square metre) and total rainfall (millimetres per square metre), along with the site latitude and the crop sowing date.

As the model parameters were selected based on optimal and favourable growth and development indices observed from nine intensively monitored crops of winter wheat across the island of Ireland in a previous study (Lynch *et al*., 2017), the estimated values of YP_w represent an achievable yield for a crop of a modern winter wheat variety in the context of optimum plant development. Therefore, while the parameters are calibrated by these monitor crops, a differential between the estimated YP_w and the observed yield, along with the dynamics of growth and development, at each site can be expected, although a significant relationship between the estimations and observed values would also be expected if the WWYPM parameters were an accurate reflection of the interaction between meteorological variables and yield formation.

The observed yields of the monitor crops, grown with crop management that aimed to minimise crop stress across Ireland from 2013 to 2015 as described by Lynch *et al*. (2017), along with the corresponding estimates of YP_w from the WWYPM, are presented in Table 2. When only Carlow and Killeagh sites are considered (n=6), which represent sites in the south-east and south of the island of Ireland, respectively, the relationship between the observed yield in

Table 2. Observed winter wheat grain yield (t/ha; 85% DM), total biomass accumulation (t/ha; 100% DM) and GS61 date from monitor crops grown across Ireland and estimations of water-limited yield potential, total biomass and date of GS61 for these site-seasons using the WWYPM

Site[1]	Year	Sowing date	Observed			WWYPM estimated			
			Yield	Total biomass	GS61	YP_w	Total $biomass_w$	GS61	Yield differential (%)
Crossnacreevy	2013	8 November	15.8	19.2	25 June	13.5	23.6	11 July	-17
	2014	29 October	10.7	19.0	16 June	13.3	25.5	13 June	20
	2015	4 December	11.9	22.5	30 June	12.1	25.8	28 June	2
Carlow	2013	25 October	10.7	18.0	19 June	13.5	27.1	25 June	21
	2014	14 October	12.1	25.5	11 June	15.9	26.0	2 June	24
	2015	14 October	13.0	22.6	13 June	17.4	31.8	5 June	26
Killeagh	2013	23 October	15.0	22.5	18 June	19.0	31.5	2 June	21
	2014	15 October	13.4	25.9	10 June	18.2	31.5	29 May	27
	2015	6 November	13.2	24.0	14 June	18.5	31.4	2 June	29

[1]Weather data for Crossnacreevy and Carlow was obtained from weather stations within 2 km of the monitor crop site, while weather data for the Killeagh site was obtained from Roches Point, County Cork, approximately 15 km south-west of the crop site.
GS = growth stage; total $biomass_w$ = water-limited total biomass potential; WWYPM = winter wheat yield potential model; YP_w = water-limited yield potential.

the monitor crops and the estimated YP_w from WWYPM was significant (P=0.006, R^2=0.85), with a significant positive correlation (P=0.002; r=0.9368). However, when data from the Crossnacreevy monitor crops (north-east island of Ireland) was included (n=9), the relationship (P=0.242; R^2=0.07) and correlation (P=0.121; r=0.4350) between observed yield and estimated YP_w were not significant. In the Crossnacreevy monitor crop, in 2013, the estimated YP_w was 17% lower than the observed yield. At this site, the observed thermal time between sowing and GS30 was 998 degree days, which was 120 degree days shorter than the standard thermal time duration for the same phase used in the WWYPM, which resulted in a lower potential GAI and a later estimation of GS61 (16 d), while the GS69–GS87 phase of the monitor crop was also 123 degree days longer than the standard thermal time used in the WWYPM. When Crossnacreevy 2013 was omitted from the monitor crop yield data (n=8), the relationship (P=0.006; R^2=0.70) and correlation (P=0.003; r=0.8601) were significant. On average, across this data, the estimated YP_w was 21% greater than the observed yield. The estimated dates of GS61 and GS87 were 7 d prior (root-mean-square error = 11 d) and 3 d after (root-mean-square error = 9 d) the dates observed in the monitor crops. Furthermore, when estimations of YP_w were conducted using an estimation of canopy based on only calendar date from observed GAI values in the Lynch *et al*. (2017) monitor crops, the relationship between observed yields of the monitor crops was less significant (R^2 =0.37) than the WWYPM estimation (R^2 = 0.70), highlighting the benefit of including the thermal time relationship with GAI for increasing the model's sensitivity to fluctuations in climatic conditions.

Validation

Van Ittersum *et al*. (2013) highlighted the importance of validating YP_w estimates against data from crops that were managed to a level conducive to the promotion of YP_w. Sources of such data are not widely available for Irish crops; thus, two approaches to model validation are listed herein. They include analysing the relationship between YP_w estimates from the WWYPM and (i) average reported farm yields and maximum reported farm yields on a per county per year basis and (ii) maximum reported yields at five DAFM variety evaluation sites for national recommended list trials between the years 2008 and 2014. All statistical analyses were conducted using the statistical software package Genstat version 14.1 (VSN International Ltd., Hemel Hempstead, UK).

Regional average yield data

Data on the annual average farm yield and the annual maximum farm yield for seven counties or regions (Carlow, East Cork, Dublin, Donegal, Kerry, Meath and Westmeath) was collated by tillage crop advisors for the period 2007–2016. Simulations of WWYPM were conducted for counties in years where the required meteorological data recorded at a weather station within each region was available, and the relationship between average or maximum farm yield and the estimated YP was determined as an indication of the robustness of the WWYPM to accurately account for fluctuations in climate. Significant positive relationship (n=41; P=0.001; R^2=0.22; Figure 1) and correlation (P=0.001; r=0.4907) were observed between the estimated YP_w from the WWYPM and the average reported farm yields, while the maximum reported annual farm yields had a weak relationship (P=0.050; R^2=0.08) and correlation (P=0.050, r=0.3248) with the estimated YP_w. The significant relationship between average reported farm yields and YP_w estimates indicates that the WWYPM can account for the variation in climatic conditions between seasons and locations to a reasonable degree, as variability between these two measures is always present and will prevent a strong relationship due to on-farm variation in soil management, water availability, crop management, micro-climates and crop end uses. Although it could be hypothesised that the maximum reported county yield is a more accurate representation of YP_w, it seems logical that average county yields are a better reflection of seasonal and spatial variations than maximum reported county yields due to increased sample size in these values, with maximum reported yields only relating to one field and thus allowing for greater variability in terms of soil profile, distance from the weather station and crop management.

Indeed, when simulations for counties that were based on weather stations that were within a 5 km radius of the coast (i.e. Dublin, Donegal and Kerry) were excluded, the relationship and correlation between average reported county yields (n=25; P<0.001; R^2=0.53; r=0.7808) or maximum reported county yields (n=22; P<0.001; R^2=0.45; r=0.6929) and the estimated YP_w from WWYPM were more significant. This is likely a reflection of the increased temperatures and radiation levels at coastal sites in Ireland (Sweeney, 2014) and the increased agricultural area within counties that are greater than 5 km from the coast. Furthermore, when the relationship between average county yields for these sites and both the average daily temperature and the total incident solar radiation during June and July was evaluated by multiple linear regression (n = 22), a significant effect of both temperature (P = 0.03) and radiation (P < 0.001) was observed, indicating that while radiation in these summer months had the largest effect on crop yield, temperature also had an influence.

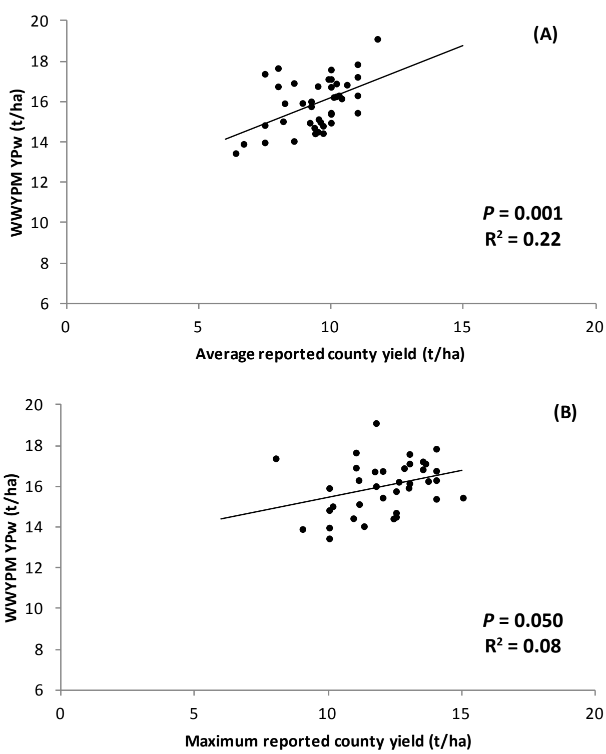

Figure 1. Relationship between the estimated water-limited yield potential (YP_w; t/ha; 85% DM) and the corresponding average annual county yield (A; n=41) or the maximum annual county yield (B; n=37) for data from seven weather stations (Oak Park, Dublin Airport, Moorepark, Mullingar, Finner, Valentia and Dunsany) in years within the range 2010–2016. DM = dry matter; WWYPM = winter wheat yield potential model.

Maximum variety trial yield data

For variety trial sites that were within a 20 km radius of a weather station that measured the required WWYPM input variables, the relationship between the maximum observed plot yields at a site and the estimated YP_w from the WWYPM was evaluated. These trial sites that also corresponded with the required local weather data were located in Cork (2012–2014), Carlow (2014), Kildare (2007–2014), Meath (2012), Tipperary (2010–2014), Waterford (2008–2014) and Wexford (2008). A significant positive relationship (n=26; P<0.001; R^2=0.52; Figure 2) and correlation (P<0.001; r=0.732) were observed between maximum trial yields and the estimated YP_w from the WWYPM; however, YP_w values were consistently higher than the observed maximum yields in the variety trials.

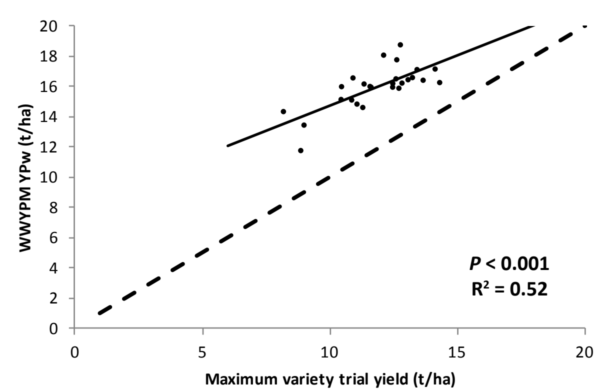

Figure 2. Relationship between the maximum yield from the annual national variety recommended list trial sites and the estimated YP_w (t/ha; 85% DM; n=26) for data from nearby weather stations (maximum: 20 km). Solid line reflects the estimated relationship between the WWYPM estimate and the maximum trial yields; dotted line represents a 1:1 relationship. DM = dry matter; WWYPM = winter wheat yield potential model; YP_w: water-limited yield potential.

This indicates that while the WWYPM model responded relatively accurately to fluctuations in meteorological variables, crops were likely also limited by factors not included in the model, resulting in a yield less than what could be achieved with the theoretical optimum crop development and growth for a modern variety that the WWYPM simulates.

Therefore, while the validation of the WWYPM is challenging due to the theoretical nature of estimating YP_w, the lack of data on maximum yields across Ireland and the limitations in weather station location and number, it can deduced from the relationships discussed herein that the WWYPM can account for the variation in weather across years and regions for the range of contrasting environments that occur across the island of Ireland and that it is a useful methodology to determine spatial differences in YP_w in a given year.

WWYPM simulation

Estimation of winter wheat grain YP_w in Ireland

Daily long-term average meteorological data for 12 sites at spatially contrasting locations across Ireland was collated for the period 1979–2008 to represent the typical weather at these sites (Table 3). As direct measurements of incident solar radiation were unavailable at some sites, estimates of solar radiation were calculated using DL and sunshine hours by the method described by McEntee (1980). Variations in the average daily temperature, total accumulated radiation and total rainfall between the evaluated sites were lower for the period 1 May–31 August than the earlier-evaluated periods and were in the range of 12.9–14.7°C, 18.5–20.7 MJ/100m^2 and 247–394 mm/m^2, respectively. Total rainfall among sites (coefficient of variation, CV = 26% and 25%) varied to a greater extent than the average temperature (CV = 7% and 9%) or total solar radiation (CV = 7% and 4%) for the 1 September–31 December or 1 January–30 April periods, respectively.

Simulations of the WWYPM were subsequently conducted using a sowing date of 1 October at each site (Table 4). Two simulations per site were conducted to assess potential differences in soil water capacity, one at a PAWC of 205 mm/m^2 to represent a soil with high water-holding capacity ("heavy") and another at a PAWC of 146 mm/m^2 to represent a soil with low water-holding capacity ("light"), relative to the typical soils present across Ireland and the UK (Rowell, 1994).

The WWYPM simulations indicated that all evaluated sites had the potential to achieve the maximum GAI of 6.7 when sown on 1 October. The size of the ranges in the estimated dates of GS31, GS61 and GS87 were 5, 5 and 10 d, respectively. The earliest estimated date for GS61 and GS87 was observed at

Table 3. Long-term averages of meteorological indices for stations that are spatially contrasting locations of Ireland from 1979 to 2008

		Average daily temperature (°C)			Total incident solar radiation (MJ/100 cm^2)[1]			Total rainfall (mm)		
Site[†]	Co-ordinates	1 Sep–31 Dec	1 Jan–30 Apr	1 May–31 Aug	1 Sep–31 Dec	1 Jan–30 Apr	1 May–31 Aug	1 Sep–31 Dec	1 Jan–30 Apr	1 May–31 Aug
Malin Head, Donegal	55.4°N; 7.3°W	9.6	6.6	12.9	5.4	7.9	19.8	448	361	303
Clones, Monaghan	54.2°N; 7.2°W	8.6	6.2	13.3	6.1	8.3	18.5	361	308	300
Belmullet, Mayo	54.2°N; 10.0°W	9.9	7.3	13.4	5.9	8.3	19.7	524	401	318
Claremorris, Mayo	53.7°N; 9.0°W	8.6	6.2	13.3	6.1	8.3	18.5	485	400	320
Mullingar, West-meath	53.5°N; 7.3°W	8.4	5.9	13.3	6.8	8.8	19.7	368	308	294
Dublin Airport, Dublin	53.4°N; 6.2°W	9.2	6.4	13.7	6.4	8.4	19.7	284	222	252
Baldonnel, Dublin	53.3°N; 6.4°W	9.0	6.3	13.7	6.9	8.9	20.1	284	218	247
Birr, Offaly	53.1°N; 7.9°W	8.9	6.4	13.7	6.2	8.3	18.9	318	260	266
Kilkenny City, Kilkenny	52.7°N; 7.2°W	9.0	6.5	13.9	6.4	8.6	19.7	336	272	261
Shannon, Clare	52.7°N; 8.9°W	10.0	7.4	14.7	6.4	8.7	19.4	381	318	280
Cork Airport, Cork	51.8°N; 8.5°W	9.4	6.6	13.5	6.7	8.8	20.7	492	406	334
Valentia, Kerry	51.9°N, 10.4°W	10.7	8.0	13.9	6.3	8.6	20.0	645	516	394

[†]Meteorological data: courtesy of Met Eireann.
[1]Incident solar radiation estimated from sunshine hours and latitude by the method of McEntee (1980).

Table 4. Winter wheat YP_w and crop development estimates from the WWYPM for spatially contrasting locations of Ireland, based on long-term average weather data

Site	Grain YP_w (t/ha)[1]		Estimated development dates[2]		
	Heavy soil	Light soil	GS31	GS61	GS87
Malin Head, Donegal	17.9	16.7	17 April	31 May	29 July
Clones, Monaghan	16.0	16.0	18 April	31 May	26 July
Belmullet, Mayo	17.3	17.3	18 April	29 May	26 July
Claremorris, Mayo	15.9	15.9	18 April	31 May	27 July
Mullingar, Westmeath	16.8	16.8	19 April	1 June	27 July
Dublin Airport, Dublin	16.9	13.5	19 April	31 May	26 July
Baldonnel, Dublin	16.8	12.0	19 April	1 June	26 July
Birr, Offaly	16.0	16.0	21 April	31 May	25 July
Kilkenny City, Kilkenny	16.1	15.1	20 April	31 May	24 July
Shannon, Clare	15.6	15.6	20 April	28 May	20 July
Cork Airport, Cork	17.6	17.6	20 April	1 June	27 July
Valentia, Kerry	16.9	16.9	21 April	30 May	25 July

[1]85% dry matter content: heavy soils represent simulations with an AWC of 315 mm, while light soils represent simulations with an AWC of 225 mm. Simulations based on long-term average meteorological data from 1979 to 2008.
[2]Zadoks *et al*. (1974).
AWC = available water capacity; GS = growth stage; WWYPM = winter wheat yield potential model; YP_w = water-limited yield potential.

the Shannon site (28 May and 20 July, respectively), while Malin Head had the latest estimated GS87 date (29 July) and was one of the sites with the latest GS61 date (31 May) along with five other sites. This resulted in a range in the GS61–GS87 period of 53 (Shannon) to 59 (Malin Head) d.

For WWYPM simulations of crops that were grown on soils that had a PAWC corresponding to heavy soils, the mean grain YP_w was 16.7 t/ha and ranged from 15.6 t/ha (Shannon) to 17.9 t/ha (Malin Head), which reflected a CV of 4.2%. Estimations of YP_w that used a PAWC corresponding to a "light" soil differed from the estimations that used a "heavy" soil PAWC at four of the 12 evaluated sites (Malin Head, Dublin Airport, Baldonnel and Kilkenny City). The magnitude of this difference ranged from a 1.0 t/ha reduction at Kilkenny City to a 4.8 t/ha reduction at Baldonnel.

Discussion

Previous estimates of winter wheat yield potential (either water-limited or -unlimited) in Ireland have been rare and relatively varied. The mean estimated YP_w of 16.7 t/ha at 85% dry matter (DM) reported in the current study is greater than the range of values previously reported for Ireland in studies that estimated YP across Europe. Supit *et al*. (2010) reported water-unlimited YP of 12.2 t/ha at 100% DM (14% lower than WWYPM estimates) for a 30 yr average from 1976 to 2005, while Boogaard *et al*. (2013) estimated that the YP_w for Ireland based on similar long-term weather data was between 10 and 11 t/ha at 100% DM (22%–30% lower than WWYPM estimations). For both these studies, estimations were calculated using the WOrld FOod STudies (WOFOST) crop simulation model, which also primarily operates based on temperature and radiation data, but which also includes estimations of an adjustment for respiration requirements and a more detailed canopy formation simulation. Values for canopy size and total biomass production reported for Ireland by Boogaard *et al*. (2013) generally seem to conform with the average values observed for high-yielding Irish winter wheat crops (Lynch *et al*., 2017), with the higher estimates of YP_w in the WWYPM likely a reflection of a higher assumed RUE value and increased partitioning of late-season assimilate to grain yield. The RUE and assimilate partitioning parameters in the WWYPM were selected to represent the highest observed values for the monitor crops used for model calibration, which are greater than previous observed values for UK crops (Sylvester-Bradley *et al*., 1998; Lynch *et al*., 2017).

In contrast, the estimated mean YP_w of 16.7 t/ha is also lower than the range of values reported previously for regions of Ireland by Burke *et al*. (2011; 22.8 t/ha at 15% DM, 37% higher than the WWYPM estimate) and Sylvester-Bradley and Kindred (2014; 19–21 t/ha at 85% DM for Northern Ireland, a 14%–26% higher estimate than the WWYPM estimate for the island of Ireland). These differences are likely due to calculations for these estimates being mainly based on the variation in total incident solar radiation and rainfall between sites and the potential amount of biomass that could be assimilated by a crop with maximum achievable light interception and partitioning to grain. They are not, therefore, sensitive to alterations in temperature during the season and the potential variance of weather within the season, which are considered in the WWYPM. However, the difference between the WWYPM YP_w estimations and these higher YP estimates are an indication of the potential increased yield that could be achieved above current genotypes with optimal growth and development, if breeding developments allowed for earlier canopy expansion and delayed senescence, as well as the ability to partition the resultant assimilate to the grain.

Due to the small area of the Republic of Ireland relative to the UK and continental Europe, it is not surprising that previous studies have reported a limited range of variation in YP_w across the country, with single national mean values reported (Supit *et al*., 2010; Burke *et al*., 2011) or estimations for different locations in the country being within a range of 1 t/ha of dry yield (Boogaard *et al*., 2013). While results from the present study did indicate a greater range across the country than previously reported (2.3 t/ha between highest and lowest at 15% moisture), the variation between sites was relatively low. This largely reflected the relatively low variation in weather input data between the sites in the later phases of the growing season (1 May–31 August). All sites accumulated more than the standard degree days between the sowing date of 1 October and $DL_{14,}$ and therefore, all sites evaluated were estimated to have a maximum potential canopy size, with the subsequent variation in the average daily temperature and total incident solar radiation between sites from 1 May to 31 August being low. Thus, it is unsurprising that variation in the estimated YP_w was low, as the majority of biomass accumulation that contributes to YP_w is estimated to be produced in the 1 May–31 August period in the WWYPM, and a reduced spatial variation in irradiance during the summer has been previously reported by Stanhill (1998), when compared to the winter.

Despite a relatively low degree of variation in the estimated YP between the evaluated sites and, indeed, what appears to be low variation between regions for average farm yields when compared on a per-county basis in recent times (Teagasc, unpublished data), the factors that are limiting yield are thought to contrast spatially across the country. When simulations of WWYPM with a lower PAWC value were conducted to represent light soils with free drainage, results indicated that YP_w at sites close to Dublin Airport, Baldonnel, Kilkenny and Malin Head may be somewhat limited by rainfall if the water-holding capacity of soils is low, while western sites generally have adequate available water due to higher rainfall. These results support the findings of Holden and Brereton *et al*. (2004) that a lack of water may be somewhat limiting to plant performance for some areas of the east coast. In contrast, the WWYPM estimations of YP_w do not account for the effects of high rainfall, low drainage and excess soil moisture. These situations can severely negatively affect crop management, causing delays in sowing, reductions in nutrient use efficiency, inhibit machinery-access to crops and also cause direct negative effects to crop growth and development (Shalloo *et al*., 2004; Schulte *et al*., 2012). Total rainfall during the winter and spring months was the most variable weather factor across the evaluated sites in the present study, with some regions on the western and southern coasts having up to 126% more rainfall during these periods when compared to the eastern regions. Holden and Brereton (2004) classified these areas as high-rainfall regions in Ireland. Variable and increased rainfall in the summer likely affects the average farm yields through negative impacts on crop harvest, while the classification of many soils in the western coast regions would generally allow for an increased likelihood of excessive soil moisture (Gardiner and Ryan, 1969; Fitzgerald *et al*., 2008) which would contribute greatly to the limitations to achieving YP_w in these regions. The impact of this phenomenon is likely the primary factor contributing to spatial differences in yield gaps, along with the topography of the majority of the cereal-growing area on the east coast of Ireland (Holden and Brereton, 2004), despite favourable YPs nationwide, when based on radiation and temperature profiles.

The mild temperatures and high rainfall incidence that characterise the climate of Ireland are also very conducive to the incidence and rapid spread of *Septoria tritici* blotch (STB), caused by *Zymoseptoria tritici,* which is the foliar disease that has the most destructive effect on winter wheat yield in North-western Europe (Jess *et al*., 2014; O'Driscoll *et al*., 2014). As such, winter wheat crops in Ireland are typically heavily reliant on extensive fungicide programmes and other cultural disease prevention strategies, such as delayed sowing and the use of resistant varieties (O'Driscoll *et al*., 2014), which may reduce achievable yield. Furthermore, the high level of biomass produced in Irish winter wheat crops, coupled with high rainfall and the potential high wind speeds of the maritime climate, often results in Irish winter wheat crops being susceptible to lodging. Berry and Spink (2012) reported the significant impact that lodging can have on crop yield, and as such, the incidence of lodging and the adjustment of crop management to prevent it (e.g. reduced nitrogen rates) may contribute to the gap between harvested yield and YP_w. In addition, a recent study indicated that up to 75% of Irish soils are outside the optimum ranges for one or more of the major macronutrients or outside of the optimum pH range for optimum crop growth and development (Lalor *et al*., 2013). Therefore, soil fertility is also likely a major contributor to the gap between average winter wheat yields and YP_w across Ireland.

For crops that yield close to the YP_w ceiling, increasing yields further can be more difficult due to the accumulation of issues that have small impacts on yield and reducing likelihood that addressing these issues would be profitable (Van Wart *et al*., 2013). If the average farm yield of winter wheat in the Republic of Ireland for the 10 yr period of 2006–2015 (9.37 t/ha) is considered the standard yield for the country, this indicates that an average of 44% of YP_w is not realised on farms, based on the average winter wheat YP estimated for 12 contrasting sites using the WWYPM. When compared to the maximum-recorded yields in their corresponding regions, the recorded average farm yields were 22% lower for a range of selected counties between 2009 and 2015 (n=41, unpublished data). This differential can be used as a crude estimate of the yield gap between the average farm yield and well-managed crops grown on favourable soils, and it indicates that significant increases in yield can still be achieved for much of the Irish winter wheat area with optimum crop management. However, combating the factors that limit the remaining proportion of the yield gap may be more difficult to address in a profitable manner without technological advances. In order to spatially estimate the differential between farm yields and YP_w, as well as to identify whether the factors that limit yield vary regionally across Ireland, a more spatially detailed assessment of winter wheat YP is required.

Conclusion

The WWYPM estimates the maximum yield that can be attained at an evaluated site for a modern winter wheat variety, based on favourable crop development and RUE, using daily temperature, radiation and rainfall data. Validations indicate that the model is sensitive to annual and regional variations in weather conditions. Estimations of YP_w indicate that the majority of sites in Ireland have the potential to grow high-yielding crops of winter wheat (> 15.6 t/ha), when the effects of very high rainfall are not considered.

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